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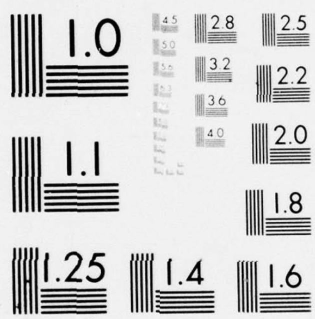

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6 WAVE ACTION AND BOTTOM MOVEMENTS IN FINE SEDIMENTS.

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CHAPTER 69

WAVE ACTION AND BOTTOM MOVEMENTS IN FINE SEDIMENTS

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Abstract

Mudbanks have been observed to have an extraordinary calming effect on the sea surface. In certain cases this effect is due primarily to the transfer of energy through the sea/mud interface and its frictional dissipation within the bottom sediments. This paper describes an experiment that measured wave characteristics and the resulting sea floor oscillations in an area where the bottom is composed of fine-grained sediments. The energy lost by the waves at the position of the experimental setup is calculated and compared with a direct measurement of the net energy lost by the waves in going from the point of the experiment to a station 3.35 km inshore. Results show that bottom motions in the range of wave-induced bottom pressures from near zero to 2.39×10^3 Pascal have the appearance of forced waves on an elastic half space. The apparent effect of internal viscosity is seen in a phase shift between the crest of the pressure wave and the trough of the mud wave. Measurements show this angle to be 22° (±11°) for the peak spectral component (T = 7.75 seconds). The energy lost to the bottom by the waves at the field site was found to be at least an order of magnitude greater than that resulting from the processes of percolation or that caused by normal frictional effects. This newly observed mechanism for the dissipation of wave energy is particularly important for waves in intermediate-depth water and could be a prime factor in determining design wave heights in muddy coastal areas.

Introduction

The extraordinary calming effect that mudbanks exert on surface waves has been recognized for at least two centuries. With the development of the offshore oil industry there also came a recognition that large vertical and horizontal dislocations of the sea floor could occur in areas where the bottom is composed of fine-grained sediments. That these large-scale movements might be linked to wave activity was dramatically suggested in 1969 when two oil platforms were toppled during Hurricane Camille (Sterling and Strohbeck, 1973). The problem of fine-grained sediment mass movements has led to both theoretical and laboratory studies of the interaction of surface-wave-induced bottom pressures and fine-grained sediments. However, direct measurements of wave-induced pressures and resulting bottom movements have not been reported prior to our work.

The results of our work describing the response of bottom sediments to wave pressures were first presented by Suhayda et al, (1976). The analysis of the field data presented here concentrates on the effect that this interaction has on the loss of wave energy. In the area where our study was conducted (see Fig. 1), the sediment concentration of the water column was not a significant factor contributing to the loss of wave energy. It has been suggested that water column sediment concentration is the key factor in the calming effect of mudbanks (Delft Hydraulics Laboratory, 1962); however, the forcing of a mud wave by wave-induced pressures is also a part of the physical processes wherever fine-grained sediments occur. An understanding of this process is important not only in the Mississippi Delta but also in such coastal areas as the Guianas, the northern coast of China, and southwest India, where extensive areas of fine-grained sediments occur.

Methods

As a cooperative research effort by scientists of the Marine Geology Branch, United States Geological Survey, Corpus Christi, Texas, and the Coastal Studies Institute, Louisiana State University, two field sites were instrumented in East Bay, Louisiana. The primary experimental station and the location of a nearby soil boring are shown in Figure 1.

Results of analysis of the boring (Fig. 2) show the bottom sediments to be very soft, recently deposited material from the Mississippi River. Shear strengths range from 1.57 kilonewtons/meter^2 (kN/m^2) near the water/sediment interface to 2.36 kN/m^2 3 meters into the sediment. These low values of shear strength are common in the Mississippi Delta. The boring log shows no evidence of the crust zone that often occurs in these sediments between -3 and -10 meters. In places where the sharp increase in shear strength that defines a crust zone occurs, it is convenient to model the physical system as a light Newtonian fluid overlying a dense, non-Newtonian fluid with a rigid bottom.

The measurement of bottom movement was complicated by two factors. First, the measurements had to be made away from a platform to ensure that the motion of natural muds would be measured. Secondly, bottom motions under typically encountered wave conditions were thought to be small, and therefore high resolution was needed. Both problems were overcome by burying accelerometers in the mud. Though displacements were around 1 cm, accelerations were such that they could be reliably measured and required no fixed reference.

Three Bruel and Kjoer type 8306 accelerometers were mounted so as to measure the accelerations in three dimensions (Fig. 3). They were placed in a water-proof cylindrical PVC housing measuring 0.215 meter in diameter and 0.635 meter in length and having a submerged weight of 5.5 kg. The housing was pushed into the mud by a diver so that the top of the package was 0.15 meter below the mud line. The electronic cable coming from the top of the package was given 4.5 meters of slack, all of which was buried in the mud, and then fixed to a taut galvanized cable that was laid along the bottom between a nearby well jacket and our main instrumented site, Platform V. Platform V, in 19.2 meters of water, is shown in Figure 4. The cable from the accelerometer was brought along the galvanized cable and up the platform leg to the recorders. The location of the accelerometer was

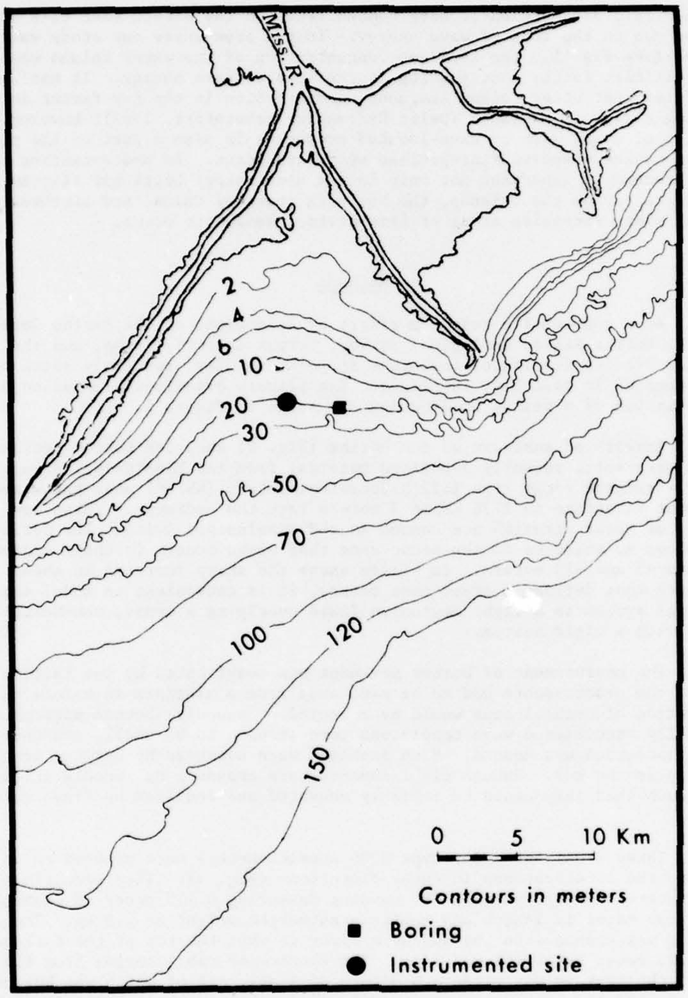


Figure 1. Location of the field site in East Bay, Louisiana.

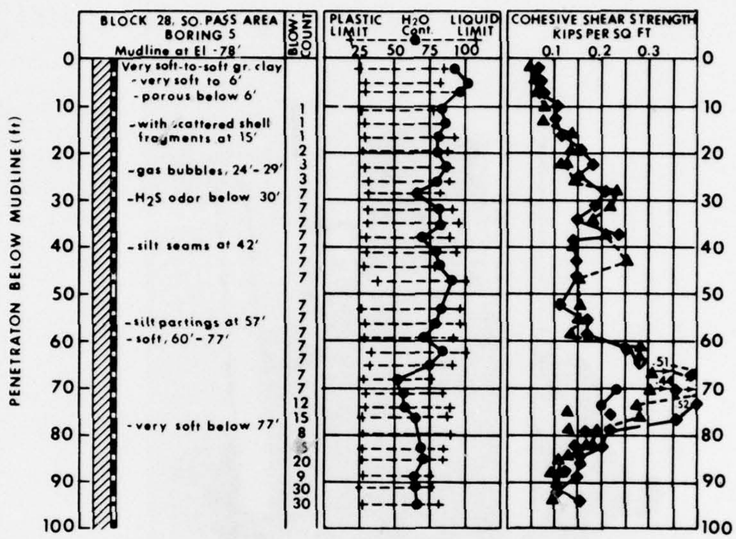


Figure 2. Results of soil boring taken near field site (1 kip/ft^2 = 48 kilonewtons/m^2). For location see Figure 1. (Boring courtesy U.S. Geological Survey, Marine Geology Branch, Corpus Christi.)

directly beneath the catwalk between the two structures so that a pressure cell attached to a weighted cable could be suspended over the package. Figure 5 is a schematic representation of the experiment and the physical system. The location of the pressure sensor was known to be within a radius of 2 meters from the accelerometer. This uncertainty in position could cause an error in the measured phase angle ϕ between the crest of the surface wave and the trough of the mud wave of $\pm 11°$ for a characteristic wave with a period of 7.75 seconds. The importance of such an error will be seen in the calculation of the dissipation of wave energy. Wave properties were measured with a wave staff, a pressure sensor, and a two-axis electromagnetic current meter attached to wire cables that were suspended from the platform and anchored to the bottom through pulleys. A system of winches and pulleys allowed us to adjust the instruments to any depth.

Platform S (see Fig. 10), 3.35 km inshore of Platform V in 5.3 meters of water, was instrumented with an anemometer, a Bendix Q-15 ducted current meter, two pressure sensors, and a wave staff. By running the instruments on Platform S simultaneously with those on Platform V it was possible to compare the net energy lost by the waves while traveling between the two data

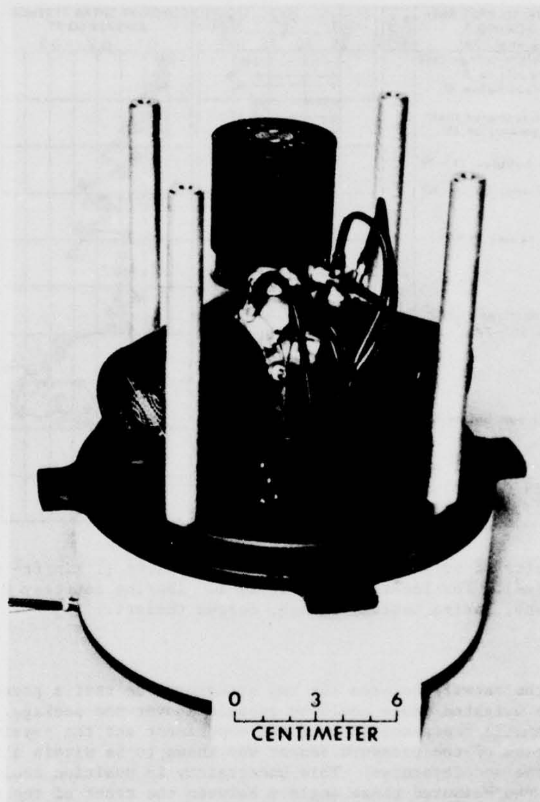


Figure 3. Array of three accelerometers.

stations with a rate of energy loss calculated from the measurements of mud movement at Platform V.

Results

Simultaneous measurements of wave height and wave-induced pressure resulted in the data represented in Figure 6. The term n is a correction

Figure 4. The main instrumented site, Platform V.

factor that matches linear theory with observed pressures and wave heights in the manner shown (where Kp = cosh k (h + Z)/cosh kh). If the observed data were in perfect agreement with linear theory, the data points would fall along the line n equal to 1.00. Further experimentation using two pressure cells placed at different depths in the water column showed that linear theory accurately predicts the change in wave-induced pressures from near the surface to within 0.5 meter of the bottom. The fact that other researchers have obtained similar results (Hom-ma et al., 1966) supported the use of a corrected linear theory for determining surface wave heights from pressure measurements made in the water column above the accelerometer. The actual values of the correction factor n that were used were those values lying along the two least squares fit lines shown in Figure 6.

A sample of the data taken in the study is shown in Figure 7. The accelerations appear sinusoidal in form and have the same general appearance as the wave record.

The shape of the bottom pressure spectrum is similar to that of the spectrum of the vertical acceleration, and the peaks occur at the same

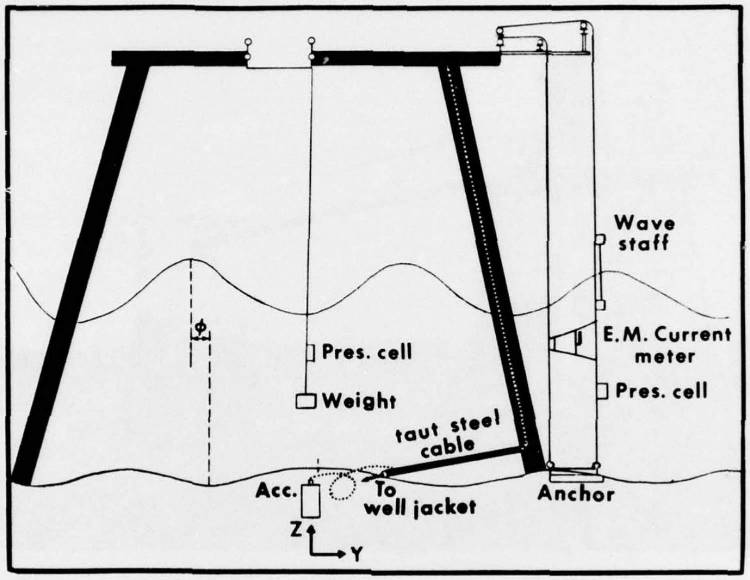


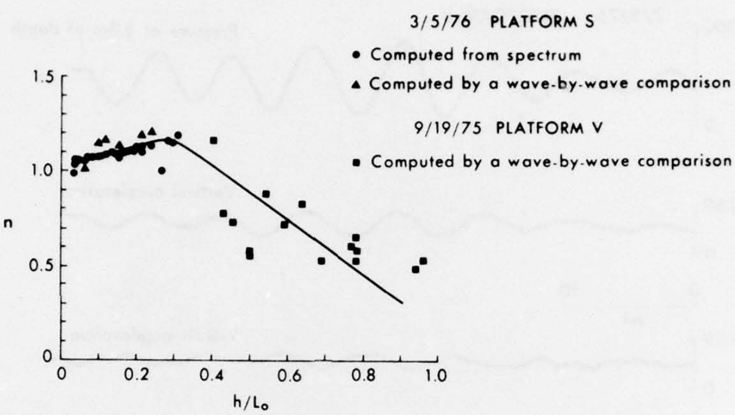
Figure 5. Experimental setup at Platform V.

frequency (Fig. 8). The low-frequency spectral components visible in the acceleration spectrum are believed to be electronic drift. (The phase angle between the crest of the mud wave and the crest of the pressure wave was 202° for the peak spectral component.) Horizontal mud motions are approximately 90° out of phase with the vertical motions, and a backward horizontal movement occurs at the crest of the bottom wave. Similar motion occurs for forced waves on an elastic half space. The ratio of vertical displacement to horizontal displacement over several sets of data averaged about 2.0.

A plot of the amplitude of the pressure wave at the bottom versus the amplitude of the mud wave (Fig. 9) reveals a roughly linear relationship for the range of pressures from near zero to 2.39×10^3 Pascal.

The average energy transmitted through the sea/sediment interface per unit and time over one wave cycle is (Gade, 1958)

$$Dm = - \frac{1}{T} \int_{o}^{T} P \frac{dh}{dt} dt \qquad (1)$$



h = depth

L_o = deep water wave length

$$n = \frac{\text{observed wave height}}{\text{observed pressure}} \rho g K p$$

Figure 6. Comparison of observed wave height and observed wave pressure with small-amplitude wave theory.

where T = wave period
P = wave-induced bottom pressure
dh = an infinitesimal increase in the height of the interface

The general characteristics of the data show that the following functions will accurately describe the motions:

$$P = Pa + A \cos (kx - \sigma t)$$

$$h = ho + MA \cos (kx - \sigma t + \psi)$$

where Pa = steady-state bottom pressure
A = amplitude of the wave-induced bottom pressure
h_o = depth of mud over which motion occurs
M = proportionality constant between the amplitudes of the mud wave and the pressure wave
ψ = phase angle between the crest of the bottom pressure wave and the crest of the mud wave

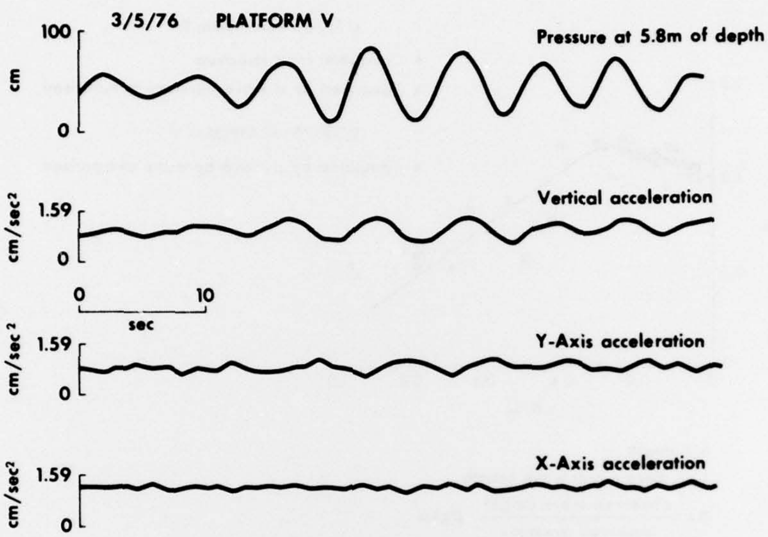


Figure 7. Sample of the data taken during the study.

After substituting equations (2) and (3) into (1) and integrating, and then using linear theory to put bottom pressures in terms of surface wave height, the equation for the rate of energy loss to the bottom is obtained:

$$Dm = \frac{\pi \rho g \; M \; H^2 \; \sin \phi}{4T \; \cosh^2 kh} \tag{4}$$

where $\phi = 180° - \psi$.

For purposes of comparison with other theories for the dissipation of wave energy, the pressure correction factor for linear theory is not incorporated into the equation. At most this can change the energy loss rate by 20 percent. From equation (4) it can be seen that the dissipation of wave energy by the soft bottom involves only two important factors, determined by the physics of the sediment movement: (1) the relationship between the pressure force on the sediment and the resultant vertical displacement, given by M, and (2) the phase angle between the crest of the pressure wave and the trough of the mud wave, given by ϕ.

The results of the two-station experiment allowed us to estimate the energy lost from the waves. Conditions during the two-station experiment

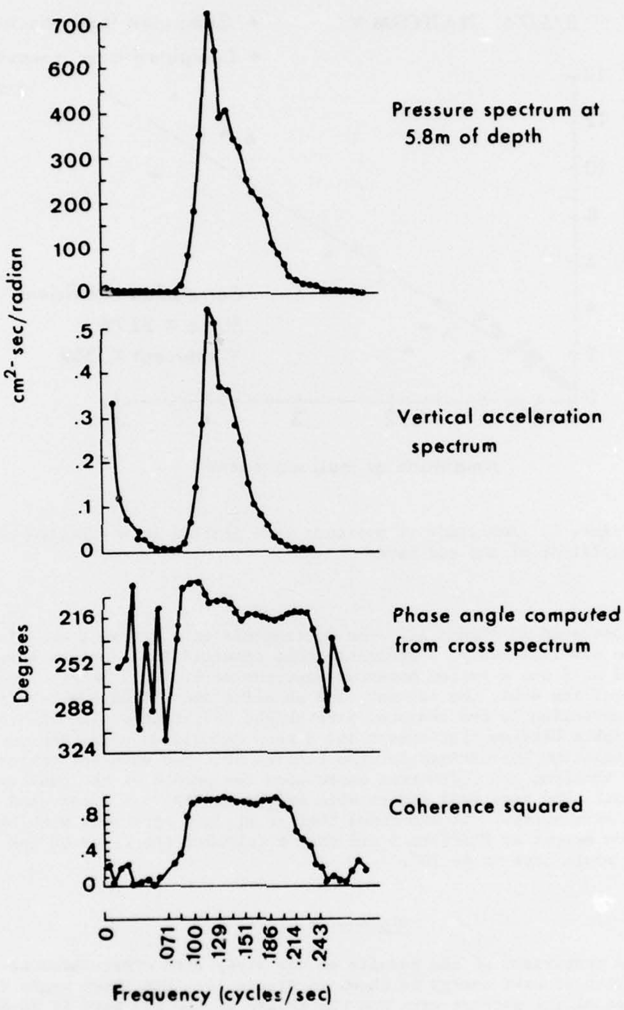


Figure 8. Results of spectral analysis of data.

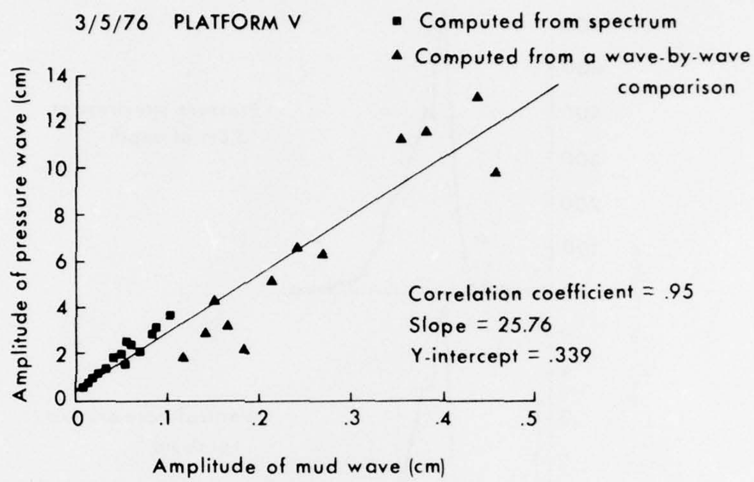


Figure 9. Amplitude of pressure wave plotted as a function of the amplitude of the mud wave.

are illustrated in Figure 10. The instruments on platform V and Platform S were run simultaneously, a procedure that resulted in a surface wave spectrum at V and at S and a bottom movement spectrum at V. For the experiment the effects of the wind, the current, and shoaling and refraction required a small correction to the measured wave height difference. The theoretical wave heights between Platforms V and S were calculated using the energy dissipation equation (4) derived for the forcing of a mud wave and taking into account shoaling and refraction based upon the period of the peak spectral component. The root mean square wave height at Platform V was used for the initial wave height. It was found that to produce agreement with the measured wave height at Platform S and keep M constant the value of the phase angle ϕ would have to be 10°.

Discussion of Results

A comparison of the results of our study with other theories for the dissipation of wave energy is shown in Figure 11. The phase angle ϕ between the crest of the surface wave and the trough of the mud wave is given two values: 22° is the angle that was actually measured at V, and 10° is the angle that results in the correct average dissipation of wave energy between Platforms V and S, assuming that M is constant. Note that the use of the smaller angle does not significantly reduce the magnitude of the dissipation

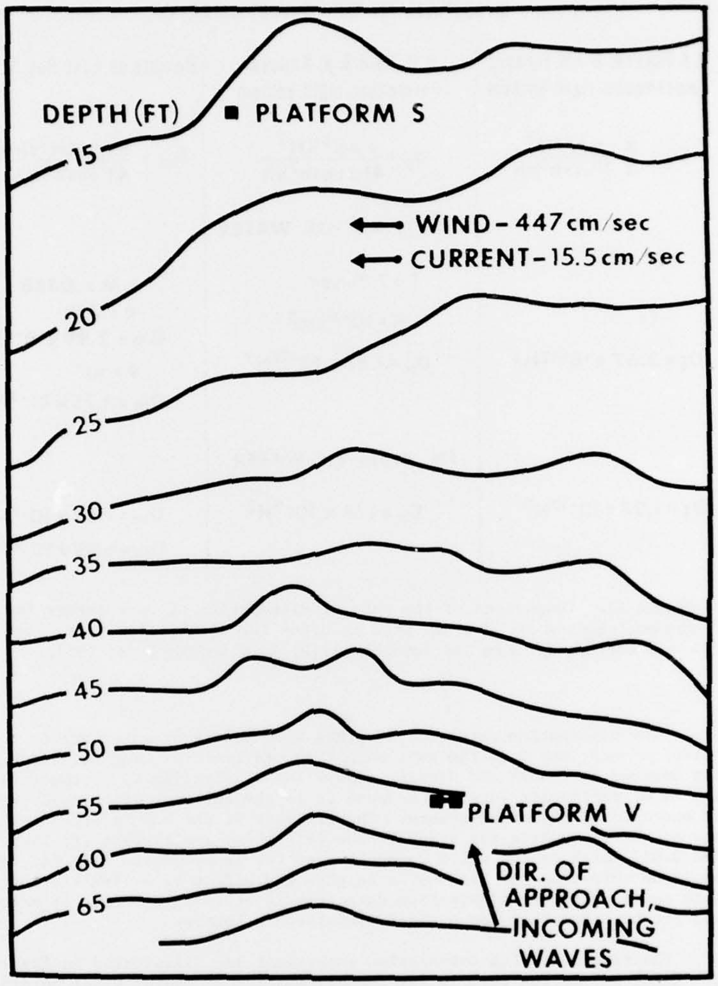


Figure 10. Conditions during two-station experiment.

DISSIPATION OF WAVE ENERGY

J.A. Putnam & J.W. Johnson Impermeable rigid bottom	R.O. Reid & K. Kajiura Permeable rigid bottom	Results of East Bay Study
$D_f = \frac{4}{3}\frac{\pi^2 \rho f H^3}{T^3 \sinh^3 kh}$	$D_p = \frac{\pi \rho g^2 K H^2}{4 L \nu \cosh^2 kh}$	$D_m = \frac{\pi \rho g M H^2 \sin\phi}{4T \cosh^2 kh}$
	IN 19.2m OF WATER	
	$T = 7.75$ sec	$M = .0388$
$f = .01$	$K = 10^{-6}\,cm^2$	$\phi = 22°$ $D_m = 2.99 \times 10^{-8} H^2$
$D_f = 3.67 \times 10^{-12} H^3$	$D_p = 1.86 \times 10^{-10} H^2$	$\phi = 10°$ $D_m = 1.25 \times 10^{-8} H^2$
	IN 4.5m OF WATER	
$D_f = 1.23 \times 10^{-10} H^3$	$D_p = 1.14 \times 10^{-9} H^2$	$D_m = 1.07 \times 10^{-7} H^2$ $D_m = 4.99 \times 10^{-8} H^2$

Figure 11. Comparison of the rate of dissipation of wave energy for the soft bottom in East Bay with theories for dissipation rates for rigid bottoms (Putnam and Johnson, 1949; Reid and Kajiura, 1957).

rate. The dissipation rates for 19.2 and 4.57 meters of water are in joules/cm^2-sec, and H is the wave height in centimeters. The relationship derived by Putnam and Johnson (1949) for dissipation by bottom friction is of particular interest because it is the one most often used even for energy dissipation on coasts. The presence of the mud is often taken into account by making the value of the frictional coefficient (f) larger than 0.01, which is the value commonly used for sandy coasts. It can be seen from this that for reasonable heights the effect of a flexible bottom is to cause an energy dissipation rate that is at least an order of magnitude greater than that for a rigid, impermeable bottom.

The results of the two-station experiment are illustrated in Figure 12. Using 10° in the formula for the dissipation of energy while holding M constant in order to make the total dissipation agree with theory is somewhat an arbitrary choice. It is entirely possible that the properties of the sediments change between V and S and cause changes in M as well as ϕ, but it should be remembered that because of the uncertainty in the

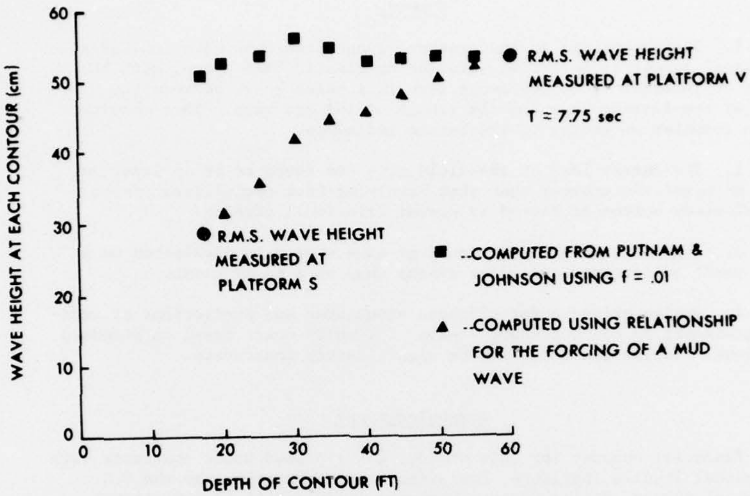


Figure 12. Comparison of the dissipation of wave energy for East Bay and that predicted using the theory of Putnam and Johnson (1949) with the measured wave height change.

position of the pressure sensor relative to the accelerometer it is possible that 10° was the true and constant phase angle.

Figure 12 also illustrates another important point concerning the dissipation of wave energy on muddy coasts. The predicted wave heights between Platforms V and S are shown in the figure as they would be predicted by Putnam and Johnson (1949). Certainly order-of-magnitude higher dissipation rates on sandy coasts can occur when well-formed ripples and the proper velocities are present (Tunstall, 1973), but even in such cases the contrasting trend, made more extreme by using Putnam and Johnson's theory, is present. By comparing the two curves in Figure 12 it can be seen that for bottom friction the dissipation of wave energy occurs mainly in shallow water, whereas for a flexible bottom a relatively greater amount of wave energy is dissipated in intermediate-depth water. Nearshore wave energy for muddy coasts can therefore be expected to be greatly reduced from that present on the outer shelf. Such coasts, in comparison to sandy coasts, tend to protect their shoreline by the dissipation of wave energy in the bottom sediments.

Summary

1. Bottom motions in the pressure range from near zero to 2.39 x 10^3 Pascal appear to be forced waves on an elastic half space, with the effect of internal viscosity being seen in a phase shift between the crest of the forcing wave and the trough of the mud wave. This results in the transfer of energy to the bottom sediments.

2. The energy loss at the field site was found to be at least an order of magnitude greater than that resulting from percolation over a typical sandy bottom or caused by normal frictional effects.

3. A relatively greater amount of wave energy is dissipated on a muddy coast at intermediate water depths than on a sandy coast.

4. Design criteria for offshore structures and predictions of sediment transport in the nearshore region of a muddy coast based on standard frictional dissipation rates may be significantly inaccurate.

Acknowledgments

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Mudbanks have been observed to have an extraordinary calming effect on the sea surface. In certain cases this effect is due primarily to the transfer of energy through the sea/mud interface and its frictional dissipation within the bottom sediments. This paper describes an experiment that measured wave characteristics and the resulting sea floor oscillations in an area where the bottom is composed of fine-grained sediments. The energy lost by the waves at the position of the experimental setup is calculated and compared with a direct measurement of the net energy lost by the waves in going from the point of the experiment to a station 3.35 km inshore. Results show that bottom motions in the range of wave-induced bottom pressures from near zero to 2390 Pascal have the appearance of forced waves on an elastic half space. The apparent effect of internal viscosity is seen in a phase shift between the crest of the pressure wave and the trough of the mud wave. Measurements show this angle to be 22° (± 11°) for the peak spectral component (T = 7.75 seconds). The energy lost to the bottom by the waves at the field site was found to be at least an order of magnitude greater than that resulting from the processes of percolation or that caused by normal frictional effects. This newly observed mechanism for the dissipation of wave energy is particularly important for waves in intermediate-depth water and could be a prime factor in determining design wave heights in muddy coastal areas.

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